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13. ABSTRACT (Maximum 200 words) The primary focus of this effort was to demonstrate an ultrasmall optically pumped far infrared (OPFIR) laser based on a photonic band gap (PBG) crystal cavity. Conventional cylindrical copper waveguide ultrasmall OPFIR lasers were constructed and their performance properties were measured as a function of pump power, gas pressure, and cavity length. Pure and doped two dimensional PBG crystals were constructed, and their transmissivity was measured as a function of wavelength, incidence angle, crystal size, and doping configuration. A high resolution THz spectrometer based on a low temperature-grown GaAs photomixer and a mode-locked Ti:Sapphire laser was constructed and molecular spectra were measured. The amplitude and phase noise properties of the Ar ⁺ laser-pumped Ti:Sapphire were measured as a function of harmonic number using this photomixer. Finally, the photoluminescence of type-II GaAs/AlAs single quantum wells was measured as a function of well width, pump power, and temperature.				
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OPTICALLY PUMPED FAR-INFRARED LASERS
BASED ON PHOTONIC BAND GAP CRYSTALS

FINAL PROGRESS REPORT

Henry O. Everitt

July 9, 1998

U.S. ARMY RESEARCH OFFICE

DAAH04-93-D-0002

DUKE UNIVERSITY

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FINAL PROGRESS REPORT
April 1, 1993 - September 30, 1997

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Grant Number: DAAH04-93-D-0002

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Name of Institution: Duke University

1. List of Manuscripts

T.M. Goyette, W. Guo, F.C. De Lucia, H.O. Everitt, J.C. Swartz, B.D. Guenther, K.A. McIntosh, E.R. Brown, "Femtosecond Demodulation Source for High Resolution Submillimeter Spectroscopy", *App. Phys. Lett.*, **67** (25), 18 December 1995, pp. 3810-3812.

H.O. Everitt and F.C. De Lucia, "Rotational Energy Transfer in Small Polyatomic Molecules", *Advances in Atomic, Molecular, and Optical Physics*, 1995, Academic Press, Inc., pp. 331-400.

T.M. Goyette, W. Guo, F.C. De Lucia, E.R. Brown, K.A. McIntosh, K. Juvan, J.C. Swartz, H.O. Everitt, and B.D. Guenther, "High Resolution Sub-Millimeter Spectroscopy Using Mode-Locked Laser Driven Electro-Optic Antennas", *Ultrafast Phenomena X*, Springer Series in Chemical Physics, **62**, 1996, pp. 56-57.

Stroschio, M.A., G.J. Iafrate, H.O. Everitt, K.W. Kim, Y. Sirenko, S. Yu, M.A. Littlejohn, and M. Dutta, *Confined and interface optical and acoustic phonons in quantum wells, superlattices and quantum wires*, in *Properties of III-V Quantum Wells and Superlattices*. 1996, pp. 194-208.

E.R. Brown, H.O. Everitt, and J. P. Dowling, *A Practical Guide to Photonic Crystals*. In Preparation, John Wiley & Sons.

L.J. Blue, T. Daniels-Race, H.O. Everitt, R.E. Kendall, and S. J. Teitsworth, *Photoluminescence of a p-i-n GaAs/AlAs Single Quantum Well Structure under Electric Field Bias*, In preparation.

2. Scientific Personnel Supported

1. John Burk (Undergraduate, graduated 5/98)
2. Mark Sims (Undergraduate, graduated with Physics Honors, 5/94)
3. Lawrence Sorriello (Undergraduate)
4. Christine Caccamise (received MA, 8/96)
5. Linda Blue (received Ph.D., 4/97)
6. Erin Ward (Graduate Student)
7. Christopher Baird (Graduate Student)
8. Mike Hornish (Graduate Student)
9. Kim Juvan (Graduate Student)
10. John Swartz (Post Doctoral Researcher)
11. Kyle Ferrio (Post Doctoral Researcher)

3. Inventions

None

4. Scientific Progress and Accomplishments

The primary focus of this effort was to demonstrate an ultrasmall optically pumped far infrared (OPFIR) laser based on a photonic band gap (PBG) crystal cavity. Many of the proof-of-concept building blocks necessary to demonstrate this novel type of laser were demonstrated during the grant period. Conventional cylindrical copper waveguide ultrasmall OPFIR lasers were constructed and their performance properties (gain, loss, output power, slope efficiency, threshold power) were measured as a function of pump power, gas pressure, and cavity length. Pure and doped two dimensional PBG crystals were constructed, and their transmissivity was measured as a function of wavelength, incidence angle, crystal size, and doping configuration. A high resolution THz spectrometer based on a low temperature-grown GaAs photomixer and a mode-locked Ti:Sapphire laser was constructed and molecular spectra were measured. The amplitude and phase noise properties of the Ar^+ laser-pumped Ti:Sapphire laser were measured as a function of harmonic number using this photomixer. Finally, the photoluminescence of type-II GaAs/AlAs single quantum wells was measured as a function of well width, pump power, and temperature.

Ultrasmall Optically Pumped Far Infrared Laser

Since the discovery in this laboratory 12 years ago that ultrasmall optically pumped far infrared laser cavities operate at much higher pressures than previously believed possible, little further investigation of the performance of these lasers has been undertaken. One objective of this project was to measure critical laser operating characteristics (gain coefficient, cavity loss, saturation parameter, threshold, slope efficiency, output power) as a function of cavity parameters (pressure, pump power, cavity length, cavity diameter). Such an understanding is necessary in order for a PBG-based laser to be designed. Graduate student Christine Caccamise completed her Master's degree work, begun in 1994, experimentally and theoretically investigating the performance of the $^{13}\text{CH}_3\text{F}$ OPFIR laser. She built a new type of OPFIR laser cavity whose diameter was 0.5 cm and whose length could be varied continuously from 3 cm to 20 cm. She then measured the dependence of the output power of the laser as a function of pressure and cavity length in order to evaluate the dependence the threshold intensity and slope efficiency on these parameters. For a fixed length cell, the threshold intensity was seen to increase quadratically with pressure while the slope efficiency was virtually independent of pressure (Figure 1).

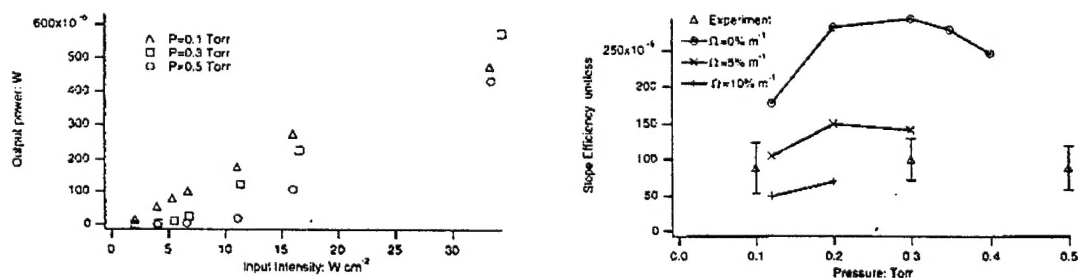


Figure 1. a) Measured output power versus input pump power for the 15 cm long $^{13}\text{CH}_3\text{F}$ OPFIR laser. b) Measured and calculated slope efficiency assuming lasing modes of differing ohmic losses. The data and others suggest the lasing mode is TE01 for this 0.5 cm diameter by 15 cm long copper laser cavity.

She subsequently developed a simple 5-level model of collisional energy transfer in $^{13}\text{CH}_3\text{F}$, complete with hole burning and pump saturation, in order to estimate the steady-state distribution of population among the salient rotational and vibrational states. This distribution was used to estimate the output power of the laser as a function of the various cavity parameters mentioned above, and from this dependence the laser operating characteristics were estimated. It was found that the operating performance of the OPFIR laser strongly depended on the ohmic losses associated with the lasing mode in the cavity. The measured slope efficiency is consistent with the ohmic losses predicted for a TE₀₁ mode in the cylindrical laser cavity. The threshold intensity was predicted to follow a quadratic dependence as observed; however, the measured values were approximately 5 times lower than predicted. This beneficial result is likely due to the non-homogeneous distribution of the pump beam within the OPFIR laser cavity. Finally, the model predicted optimal cavity lengths depending upon operating pressure and mode ohmic losses. In general, it was found that the cavity length should be shortened for increasing pressure and ohmic loss, while output power decreased with increasing ohmic losses. Clearly, there is a need for low loss OPFIR resonators such as to be provided by PBG crystal resonators.

Two Dimensional Photonic Crystal

The properties of lossless, purely dielectric PBG crystals have been calculated and measured for several years now. However, there is little theoretical or experimental work dealing with PBGs composed of lossy dielectric material and how that loss affects the transmissivity of perfectly periodic PBG crystals or the cavity Q of PBG crystals with defects. A thorough understanding of how PBG cavities could be constructed and how their properties vary as a function of construction parameters (defect placement within PBG crystal, dielectric loss, surface termination) is necessary before PBG-based OPFIR cavities can be constructed.

Undergraduate John Burk undertook an experimental investigation of two dimensional PBG crystals constructed of 0.25" dielectric rods ($\epsilon=12$) arranged in a triangular lattice with lattice constant $\approx 1\text{cm}$. As predicted, the resulting band gap occurred between approximately 5-8 GHz for one polarization (TM) for all rotational orientations of the crystal. The attenuation of the photonic crystal increased approximately 6 db for each additional row (lattice plane) of the crystal (Figure 2). However, increasing the number of rows beyond five did not further increase the attenuation because of losses in the dielectric rods and attaining the noise floor of the network analyzer. The band gap was seen to be independent of the incident angle of the radiation as the crystal was rotated through the irreducible zone.

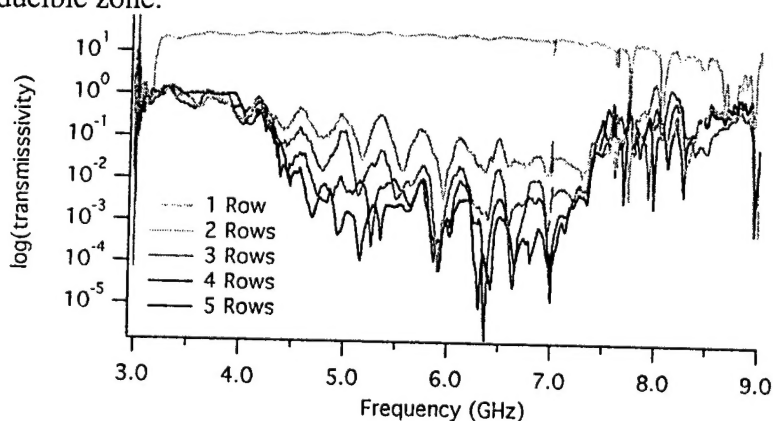


Figure 2: The transmissivity of a two dimensional triangular photonic crystals composed of dielectric rods ($\epsilon=12$) surrounded by air. The transmissivity decreases with increasing crystal thickness for normal incidence radiation. Similar data is obtained at all angles of incidence within the irreducible zone.

However, initial measurements of photonic crystals with single rod defects never revealed the expected defect cavity mode. After extensive investigation it was found that the problem lay in the quality of the dielectric rods provided by the manufacturer, Emerson Cummings. The quoted dielectric constant was $\epsilon=12, \pm 2\%$, but the measured dielectric constants of the rods varied between 11 and 15. As a result, the array of rods was not functioning as a photonic crystal but a regular array of irregular scatterers. The manufacturer replaced the defective rods with accurately characterized rods with $\epsilon=12$, and the measurements revealed the expected defect modes.

Single defects were placed in the photonic crystal, and the mode frequency and Q were measured as a function of photonic crystal width and placement of the defect within the photonic crystal. Initial indications were that, as expected, mode frequency was fairly independent of the size of the photonic crystal but was quite sensitive to the uniformity of dielectric constant in the rods surrounding the defect. By the end of the grant, measurements had begun to investigate the behavior of various types of defects in photonic crystals. A lorentzian lineshape was fit to the defect modes to measure the center frequency and linewidth, from which the cavity Q was obtained (Figure 3). Linewidth was found to increase as the defect was placed nearer the surface of the photonic crystal and to decrease as the photonic crystal was made thicker.

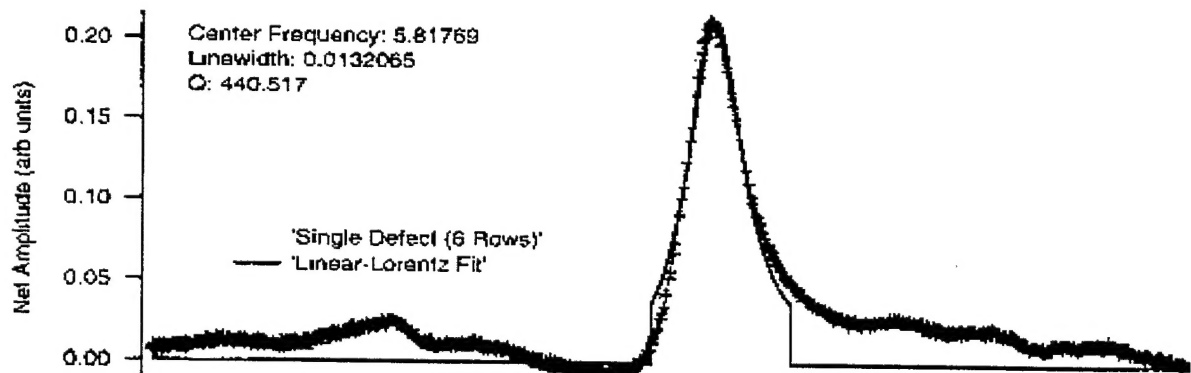


Figure 3: Defect mode of a six row, two dimensional triangular photonic crystal with a single rod removed in the center. The defect mode was measured using a network analyzer to compare the incident and transmitted microwave radiation through the photonic crystal. The solid line is a lorentzian lineshape fit to the data, revealing the center frequency and linewidth.

Channel defects placed in a line from the front to the back of photonic crystals of varying thickness were studied as a function of channel width and channel length. The ends of these so-called "waveguide" defects were also plugged with dielectric rods in order to form channel cavities, and the cavity wavelengths and Qs were measured (Figure 4). Initial indications revealed that the mode structure was more complex than would be expected for a metal waveguide of similar dimensions. This suggested that the photonic crystal surface produced a more complex, distributed feedback reflection. At the end of the grant, these data were being analyzed as a function of channel width to explore the transition from Fabry-Perot behavior (infinite width, variable length) to waveguide behavior (variable width and length) to single defect.

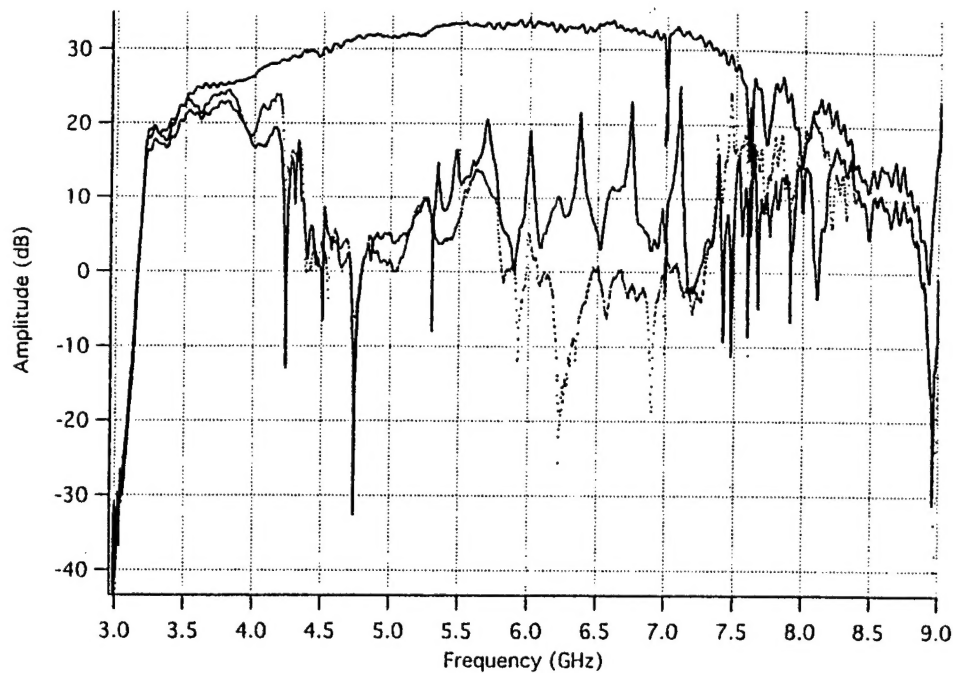


Figure 4: This 11 row photonic crystal has a 9 row long, 1 row wide channel defect centered in it. The two ends are capped with a single rod, making this defect approximate a waveguide cavity with leaky end mirrors. However, the easily discernable mode frequencies do not correspond to this geometry due to the corrugation of the PBG side walls.

THz Photoconductive Switch

Any millimeter wave PBG crystal to be used as a low-loss OPFIR laser cavity would have to be characterized. One approach being pursued in collaboration with Dr. B.D. Guenther at Duke University was to develop a novel spectroscopic tool based on photoconductive switches. These switches are derived from MIT Lincoln Laboratory low temperature-grown GaAs photomixers driven by a mode-locked Ti:Sapphire laser. These DC-biased photomixers with bowtie or complementary log-spiral antennas can generate a comb of frequencies from 80 MHz (the mode lock frequency of the laser) to >500 GHz through a process referred to as femtosecond demodulation. Collaborators at MIT Lincoln Laboratory, Ohio State University, and Duke University have developed a high frequency (>500 GHz), high resolution (<1 MHz) spectrometer by modulating the Ti:Sapphire cavity length in order to scan the appropriate harmonic of the mode lock frequency through a desired frequency span.

In 1995, a proof-of-concept demonstration measuring the location and shape of a molecular rotational absorption line at approximately 300 GHz was performed, and the results were within experimental error of the predicted values. In 1996, the photomixers were used to characterize the noise performance of the mode-locked Ti:Sapphire laser. The objective was to explore the limits of utility of this type of spectrometer. Specifically, we hoped to discover the maximum operating frequency of this spectrometer. It had been predicted that the phase noise of the Ti:Sapphire laser would cause significant broadening at high harmonic number, preventing high resolution measurements. Indeed, it was found that the phase noise of the system scaled quadratically with harmonic number above the fundamental mode lock frequency. In addition, it was found that noise on the Ar⁺ pump laser power supply was modulating the the mode lock frequency, and the sidebands observed at high harmonics dominated the phase noise. However, the total amount of noise on the system was found not to significantly broaden rotational absorption spectra at 300

GHz corresponding to a harmonic number of almost 4000. A quieter pump laser power supply could enable high resolution measurement throughout the full ~1 THz bandwidth of the photomixers.

Photoluminescence and Tunneling in GaAs/AlGaAs Single Quantum Wells

A new collaborative effort with Prof. Steven Teitsworth of Duke University resulted in the construction of a new facility in the Duke Microwave Laboratory. Graduate student Linda Blue purchased and mounted a Janis variable temperature cryostat with optical ports and assembled support equipment to perform photoluminescence measurements. A grating spectrometer and photomultiplier tube were used to measure the wavelength dependent photoluminescence of single quantum well systems in GaAs/AlGaAs excited by an Ar⁺ laser. The objective of the study was to investigate the photoluminescence in Type I (direct recombination in a 50Å well), Type II (indirect recombination in a 20Å well), and crossover (mixed recombination pathways in a 35Å well) single quantum well structures. As expected, Type II luminescence was not observed in the 20Å well due to the indirect nature of the transition. However, distinctive photoluminescence peaks were observed in the 35Å well corresponding to the crossover and mixing between Type I and Type II.

Type I and Type II infrared quantum cascade lasers are built from building blocks similar to the quantum well samples studied by Ms. Blue. Indeed, after she completed her Ph.D. work in April, 1997, she was hired by Dr. Jerry Meyer of the Naval Research Laboratory to work on infrared quantum cascade lasers. This represents a significant technology transfer from an ARO-sponsored grant to a DoD research facility.